Strategic Plan of the IVS for the Period 2016-2025

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Abstract Over the next decade, the IVS is on the cusp of dramatic changes transitioning from using large, slow moving antennas observing at S/X ("legacy" systems) to using small, fast antennas with broad-band receivers, the so-called VGOS systems. Never has there been a time when so many antennas specifically designed for geodetic VLBI are scheduled to come on line in such a short period. VGOS observing will change all aspects of VLBI, from scheduling, to correlation, to observing strategy, to analysis. Compared to current observing, a typical VGOS session will have 1–2 orders of magnitude more data. In this strategic plan we outline some of the operational concepts of VGOS observing, our goals for data accuracy and latency, and some of the challenges and issues we will face during this transition.

Keywords VGOS

1 Prolog

In the period 2016 to 2025 the International VLBI Service for Geodesy and Astrometry (IVS) will enter the era of the VLBI Global Observing System (VGOS), which will be composed of a transition period and subsequent full VGOS operations. To enable overall planning and to give the stakeholders and IVS Associates some guidelines for the investments and activities needed, the IVS Directing Board has developed the *Strategic Plan of the IVS for the Period 2016–2025*.

IVS Directing Board

This strategic plan was developed on the basis of the current composition and framework of the IVS's operations. The IVS acts as a truly international entity consisting of hardware distributed all over the world, a global organizational structure, and the associated personnel for organizing and administering the IVS. The IVS is not a formal global institution but a collaboration, which operates on a best-effort basis. The full potential of geodetic and astrometric VLBI can only be exploited if baselines beyond a length of about 6,000 km are employed for Earth Orientation Parameter (EOP) and Celestial Reference Frame (CRF) determinations. The same also applies to any Terrestrial Reference Frame (TRF) application. Because of this it would be difficult for the IVS to be replaced by a single country running its own VLBI network, operating its own telescopes, correlating and analyzing the results, and producing the final VLBI products.

In the geodetic and astrometric communities it is well known that the IVS is essential for the monitoring of the Earth orientation parameters and for the maintenance of the celestial and terrestrial reference frames. However, the IVS is little known for its products beyond this limited group. For this reason the organizational relationships of the IVS, external as well as internal, and the administration of the IVS must be developed further. In this context the IVS may benefit from the GGOS and UN-GGIM initiatives (Global Geodetic Observing System, UN-Global Geospatial Information Management), which will help to raise awareness in political circles of the needs for geodetic products. We urge IVS associates to publicize this initiative and the important role of IVS in geodesy.

Another challenge of the future is that many experienced colleagues have reached or are close to retirement age. Hence, we need active recruiting and staff structure development to replace them. An increased awareness of this issue is needed within the IVS components up to the highest level of their administrations.

On the product side, several separate requirements compete: accuracy, resolution, and timeliness. These need to be balanced for an optimum satisfaction of the product users. There may arise conflicts between what is actually feasible given the current economic and organizational circumstances and the users' desires for higher accuracy, resolution, and timeliness.

Under these premises the *Strategic Plan of the IVS for the Period 2016–2025* was developed to address the following topics and the corresponding goals for operational concepts, including correlation, product lines, and institutional relations.

2 Operational Concepts

2.1 Observing Network

Although not quite correct for a chronological consideration of the IVS's operation, the first group of components to look at is the observatories. Their technical layout was defined in Petrachenko et al. (2009) with comparisons of components documented in Petrachenko (2013a, 2013b). In summary it can be stated that VGOS telescopes should be fast slewing and capable of recording broadband radiation of extra-galactic radio sources from 3–14 GHz continuously. It is conceivable that the upper limit may even be extended to 18 GHz, which offers some advantages for the receiver developments due to the fact that 18 GHz is a multiple of the lower limit of 3 GHz. The development of a suitable feed horn needs to be followed closely, and a recommendation for a certain development line of wideband feed cannot be made at this stage. The same applies to the final frequency band allocation within the total bandwidth.

Although Ka-band (32 GHz) observations may have their benefit, they are hampered by the degradation of quality by adverse weather conditions and are, thus, not recommended for the routine monitoring purposes, which are needed by the IVS for EOP determinations.

The recently developed Mark 6 recording units were designed to cope with the expected data volume and should reach an operational stage soon. In parallel to this, commodity based recording systems, such as *Flexbuff*, are suitable for handling today's data volume but still need to prove their suitability for 16 Gbit/s recording. However, these systems are suited for asynchronous or even synchronous eTransfer operations. A firm recommendation for a particular recording system cannot and should not be given at all because the IVS should remain open for development initiatives.

The previous statement has, however, to be seen within the restrictions of technical standards since compatibility must be guaranteed throughout the community. This can be achieved only if standardization in VLBI keeps pace with the technical developments, and the IVS Technology Coordinator has a very special responsibility in this arena. The Technology Coordinator should take care that the necessary standards are developed and adopted in time and that geodesists and astronomers alike abide to these standards.

The VGOS idea as laid out in Petrachenko et al. (2013) foresees an operation of the IVS infrastructure of seven days per week for 24 hours each. This general rule should be interpreted in such a way that the VGOS operation produces EOP, especially UT1–UTC, seven days a week with a certain time resolution. At this stage the main customer, the IERS Bureau for Rapid Service and Prediction at US Naval Observatory, processes its data every six hours. The same time resolution should be attained initially for the IVS products with a goal of higher resolution, i.e., aiming for three-hour intervals. Since the determination of a single UT1–UTC value at a given epoch requires a certain observing time to gain geometrical stability, continuous observations are the necessary consequence. Additionally, since the correct estimates of UT1–UTC are dependent on the other EOP components, it is necessary to employ full-scale VGOS network observations.

The necessity for continuous network observations has led to the advantageous situations that at some observatories twin telescopes are being built. These can be used in cycles allowing sufficient maintenance and repair periods, thus guaranteeing that these observatories can really provide 24/7 operations. They will be the cornerstones of the VGOS observing network.

Such a scheme is not possible at single-telescope observatories, so we cannot expect that each and every station will observe continuously. Instead we anticipate a rotating system of telescopes joining or leaving the network for full days at a time. This will ensure that observatories where only a single telescope is available have sufficient time for maintenance and repairs.

For the constellation of the networks, it is necessary to take into account how many telescopes are available with VGOS capabilities, so there will be a clear distinction between the transition phase and full operation of the network. The initial observing setup in the transition phase with daily one-hour sessions is laid out in the VGOS Observing Plan (Petrachenko et al. 2013).

Although initial plans called for 30 stations observing simultaneously, reality will determine how many telescopes will be available at any time. However, it is the declared aim of the IVS to exploit the full benefit of at least a 24-station network. For determining the optimal locations of the telescopes, simulations can help to give guidelines. These are being carried out in, for example, the PLATO Working Group of the IAG (Thaller et al. 2015). Without preempting the results of those studies, it can be clearly noted that the IVS network lacks observatories in the Southern Hemisphere. The IVS, the IVS DB, and all IVS Associates should actively encourage and pursue the construction of new telescopes primarily in Africa, South America, and any suitable islands as far south as possible. The operations and continued participation of the rather few existing telescopes in these regions should be safeguarded because they are extremely important for continental motions and Earth orientation variations for reasons of geometric constellation and network sensitivity.

The cost of operating the VGOS telescopes is non-negligible. Automatic, unattended observations may be one way of reducing the financial burden. Remote operations of telescopes are another promising avenue to reduce costs and to allow for quick responses to unforeseen occurrences. The formation of observing control centers which hand over responsibility from time zone to time zone at normal working hours will be considered by the IVS.

Even though the primary operations of the IVS will aim at the regular determinations of EOP with the VGOS network, the so-called legacy antennas continue to be needed in the future. On the one hand, the IVS Observing Program Committee and the IVS Coordinating Center need to take care of suitable mixed-mode observations to locate the new telescopes in the terrestrial reference frame currently defined by the legacy telescopes. On the other hand, the legacy antennas mainly have larger apertures, which make them more sensitive. They are, therefore, more useful for observations of weaker radio sources and, thus, important for the maintenance of the celestial reference frame. For these purposes, as many as possible legacy antennas that satisfy the sensitivity qualification should be kept in operation for as long as possible. Their use will provide not only dedicated TRF observations but also guarantee a sufficient overlap for maintaining the long position time series of the stations and the transfer of the continental drift information to the new telescopes.

Independent of the legacy telescope CRF work, astrometry with the VGOS antennas should also be taken into account for the future. Here, the observing time available for astrometry heavily depends on the number of telescopes available at a given time. A clear projection of how much dedicated CRF observing will be carried out can, therefore, not be given at this stage.

2.2 Correlators

Correlation of the observed data is a central requirement of VLBI. Due to the fast development in commodity computing, software correlators are almost solely employed for today's VLBI correlations. Correlators are the first instance where the data can be checked, and often the data quality is far from the specifications defined in the session setup. Under the premise that observing efforts are costly, the correlator staff tries to rescue as many observations as possible and inform the stations about possible defects in their systems. Likewise they give feedback on station tests, which are necessary whenever a telescope takes up operations or has undergone major changes in its hardware.

Before correlation results can be used in data analysis, the correlator output needs to be fringe-fitted. This process is considered an integral part of correlation and requires a great deal of expertise, which in most cases has to be separated from the analysis of the group and phase delays. Today, five out of six correlators use the same suit of fringe-fitting software (difx2mark4, fourfit) although other suitable software is available. For broadening the expertise and for benefitting from modern computational capabilities, the IVS strongly encourages further developments in this field.

Several correlators currently share the load of the IVS correlation. Over the long history of VLBI correlations, expertise has been built up in multiple correlation centers such that workloads can be shifted from one correlator to another as needed. This capability will need to be maintained and exploited in the future when the steadily increasing correlator capacity requirement will need to be distributed to multiple correlator centers on an even basis. Unfortunately, the situation with funding and operating the correlators varies greatly among the individual centers. This affects not only the financial background but also technical expertise. On the institutional side, a firm commitment at the level of about ten years is needed to make credible planning feasible and to sustain correlator operations. This does not seem to be possible for some of the institutions involved but is needed to provide guarantees for continuous product delivery. The situation with experienced personnel, is equally critical. VLBI correlation is a very specialized skill, and it takes years to become proficient. While a number of correlator centers gear up their operations and learn, mostly from established groups, how to correlate and how to cope with defective data or unusual setups, the number of experienced personnel that can provide this expertise is diminishing due to aging and retirements. We need to hire and train suitable personnel on a long term basis with sufficient perspectives for the future.

The development of correlator and fringe fitting software is not the domain of geodesists alone but also of astronomers with very similar interests and sometimes more resources. Sharing the operations of a correlation facility with closely aligned disciplines (e.g., with astronomers) is a suitable model for sharing costs and experiences. Synergies should be explored to a greater extent than is done at the moment. This will help to advance the technology much further than geodesists can achieve alone. The same applies to computer scientists, who may have different interests but may be able to provide modern concepts for the ever changing world of computing.

2.3 Data Transport

Closely linked to the correlation proper are data transport issues. Here, the situation is as heterogeneous as the variety of correlators. While some of the observatories may have to ship disk modules, others would send all the data to the correlators by electronic transfer. The latter poses serious network bandwidth and storage requirements on the respective correlator if this is done by many stations. The situation will only get worse with VGOS, where a typical station will take ~ 40 TB of data during a session.

The other issue in this respect is the data transfer capability of the electronic network. Stations normally subscribe to a provider for a certain bandwidth. The same applies to the correlator with the additional requirement that the data of multiple telescopes must be transferred from the backbone to the final storage area in parallel. This requires multiples of the bandwidth of individual telescopes. In some countries, the costs for that are (still) prohibitive.

In terms of efficient operations, some optimization seems to be possible. For example, the correlator staff could initiate retrieval of the data from the telescope sites at their discretion. This would allow the correlator personnel to efficiently balance the load on the last-mile to the correlator. A second possibility is for correlators to establish high-capacity RAID systems at the backbone node and retrieve the data from there when needed. Both of these measures have their pros and cons, which must be balanced according to the respective situation.

Another option is to set up and operate correlators in a distributed architecture. This will keep the responsibility for session setups and quality control in the hands of the correlator centers but will potentially offer a way to circumvent data transfer problems. The IVS community should also think of and investigate decentralized correlation.

Finally, it should be noted that electronic transfer capacity is likely to limit what will be achievable in the VGOS era. It is hoped that commercial applications and political decisions will work in favor of the IVS's operation.

2.4 Session Planning and Scheduling

Even though a great deal of automation is foreseen for the daily session configuration and for the scheduling of the individual days, good coordination will be necessary to exploit the full benefit of the available resources. The IVS Coordinating Center and the IVS Operations Centers will continue to work closely together in the VGOS era.

Currently, geodetic and astrometric VLBI is organized in sessions, mainly of 24-hour duration. From a planning and organizational point of view this will continue, with the only change being that sessions will run from 0 h UT to 0 h UT. Planned network changes will always take place at day boundaries, i.e., only when the telescopes join or leave the observing networks. Of course, in the pilot phase as described in the VGOS Observing Plan (Petrachenko et al. 2013), some subsessions will be of only one-hour duration. For these reasons, the observing plans will be prepared in units of 24 hours also in the future.

Another aspect of session planning is that the IVS should strive for robustness of its products. The first approach to achieving robustness is to schedule a sufficient number of stations in each session. This will mitigate the effects of unforeseen station failures on the accuracy of the IVS products. In order to minimize the impact of a station failure during a session, a flexible response of the network to such a loss should be prepared for. The same also applies when severe degradation of sensitivity occurs. One of the possible solutions to both situations is dynamic scheduling, which can take effect as soon as an unplanned dropout or loss of sensitivity is reported. The exact mechanism of how this would be handled should be developed in the near future.

Another approach might be to operate several networks in parallel in order to provide the opportunity for checking the derived IVS products. However this requires access to a sufficiently large number of VGOS stations that several parallel networks with sufficient geometry can be formed.

3 Data Analysis Considerations and Product Lines

The different VLBI products have varying latency and spatial resolution requirements. The most stringent latency requirement is for EOP, and in particular, UT1–UTC, where accurate near-real-time daily or even subdaily measurements are desired (As mentioned previously, the IERS produces estimates every six hours.). In contrast, the latency and resolution requirements for the TRF and CRF are much more relaxed. For the CRF we need to measure sources only often enough to monitor their strengths, and much less frequently to measure their apparent positions. For the most part, these measurements will occur naturally as part of the regular observing, and no special efforts need to be made. Monitoring of the TRF on a daily basis can be achieved more economically with GNSS observations. In addition to the EOP considerations, continuous observations will provide improvement in overall reliability of the geodetic and astrometric VLBI observation setup. Except for the ultra-rapid products (see below) the time resolution of the IVS products will be set to three hours in order to be commensurate with the current six-hour interval of the IERS RS-PC and, additionally, be prepared for the increased resolution.

The whole process of producing geodetic results from VGOS observations is driven by the desire to deliver products which are as accurate as possible at the time the data are taken. However, there may be varying demands with respect to timeliness or precision and accuracy. Since UT1–UTC results used for extrapolations decay rather quickly, VGOS results should be available almost instantly. Since continuity is predominantly determined by the observing capabilities, it is a prerequisite that the processing of the observations cope with this pace by a high level of automation in data analysis. The analysis groups within the IVS always strive for highest quality. Thus it is expected that accuracy and precision will continue to improve based on changes in analysis strategies state-of-the-art modeling and processing. Furthermore it is anticipated that every IVS Analysis Center will be able to perform its analyses from the correlator output onwards so that there will be no dependence on other analysis centers.

Another criterion to be considered is latency, which means how quickly VLBI products are made available to the scientific and user communities. Latency and accuracy are not necessarily in conflict, but in general low latency (quickly available) results are mostly less accurate than those that are delivered after some longer processing and quality control time. One of the reasons is that low latency always requires some compromises with respect to the usage of auxiliary data. These might not be available instantly because they may be provided at the required quality only by another service that does not have the same latency requirement. As mentioned above, depending on the priorities, timeliness may be more important than accuracy for some users. This results in a need for products with different latencies and respective qualities.

Low latency is most important for Earth orientation parameters (EOP), which are used by the scientific and technical community. In particular, the GNSS community needs the UT1–UTC product in near-real-time (Bradley et al., 2015). Low latency is less critical for telescope coordinates, which, to a first approximation, evolve linearly. In this case, measuring telescope coordinates periodically and processing them in less than real-time may be sufficient. An exception to this might be if something abruptly changes the telescope coordinates (e.g., an earthquake) in which case we might want a rapid update and regular measurements thereafter until the station returns to a predictable motion. It should be noted that since the quality of the estimated EOP strongly correlates with that of the station positions, it is important that we have good station positions for those stations involved in EOP measurements of only one hour duration. Analyzing 24-hour sessions for EOP automatically provides good information on station coordinates simultaneously.

The processing steps and their time requirements depend on how the data transport and the correlations are carried out. For this reason two different scenarios need to be considered. The first one relies on a continuous, though retarded, correlation process. Here, the observables may be available on a scan by scan basis. This situation allows for an incremental analysis employing filter solutions with update intervals from a few minutes to virtually any length. In the second scenario, correlations are carried out in batches of three or 24 hours each with some non-negligible delay time.

Finally, in addition to striving always for highest accuracy and precision continuous development of better technical components as well as improvement in analysis strategies and models must be a standing goal of the IVS. In the context of VGOS operations, with technology and analysis always staying state of the art, the accuracy of products achievable clearly depends on the latency time permitted for the results to be available after the observations. For this reason, four different lines of IVS products are foreseen, as specified in Table 1. We emphasize that this lists our goals for the final VGOS network and is not applicable to the transition time.

In this four-level scheme, if immediate correlation is possible on a scan by scan basis and these scans are exported instantly, ULTRA-RAPID PRODUCTS will be produced from the accumulated observations. This will be a task for analysis centers with dedicated processing facilities that can be devoted to this task. Only one IVS Analysis Center can be the official IVS Real-time AC, but there should be at least one backup and control AC.

The RAPID PRODUCTS will use data of observing periods of predefined lengths. Assuming correlation in batches of three hours, these new data can be added incrementally to the preceding set and analyzed accordingly. If the correlation of these sessions only commences at the end of the 24-hour periods, the observables will not be available until a certain time after these sessions.

In order to minimize latency, the rapid products will be produced by a completely automated process at multiple analysis centers at the time of data availability. These centers may use different software packages and analysis philosophies. At that time, auxiliary files, like log files or those for the Vienna Mapping Function, may often not be available and model values will have to be used. Ideally, the output of the individual analysis centers will be combined at the level of results by the IVS Combination Center in order to ensure quality and to safeguard against mistakes. Outliers will be rejected outright with no further consideration. For this, state-of-the-art statistical techniques for outlier detection will have to be applied.

The processing line for the INTERMEDIATE PRODUCTS will permit the use of some level of intervention and the application of additional information, such as the Vienna Mapping Function and meteorological data from sources other than those provided routinely. The combination may also be carried out in a more sophisticated way, e.g., on the basis of normal equation systems or permitting re-weighting by variance component estimation. It is expected that these products will be more accurate.

The FINAL PRODUCTS for a single week should be available on the Wednesday of the subsequent week. Two days will be allocated for the analysis centers, while the remaining day will be at the discretion of the IVS Combination Center.

In terms of reading the delivery and update times in the table an example for the intermediate products with continuous correlation would be as follows: every day at 1200 UT (update epoch) the IVS will deliver updated results for the epochs 3, 6, 9, 12, 15, 18, 21, and 24 UT of the preceding day with the last data point (24 UT) having a latency of 12 hours.

Independent of latency requirements, the analysis of VGOS data will put severe demands on the capabil-

Table 1 Products, update rates, latencies, and accuracies.

Product	Product epoch	Update epoch	Epochs to be updated	Latency of last data point	Sub-product	Expected accuracy (WRMS)
Ultra-rapid	Every 30′	Every 30′	t−30′…180′	30 min.	UT1–UTC	7 µs
Rapid with continuous near-realtime correlation	Every 3 h at 3, 6, … 24 h	Every 3 h at 0, 3, 6, … 21 h UT	t−3…24 h	3 hrs	UT1–UTC	5 µs
					Polar motion	75 µas
					Nutation offsets	75 µas
Rapid with batch correlation of 3 or 24 h blocks	Every 3 h at 3, 6, … 24 h	Once every correlation data release	t−3…24 h	3–6 days	UT1–UTC	5 µs
					Polar motion	75 µas
					Nutation offsets	75 µas
Intermediate with continuous near-realtime correlation	Every 3 h at 3, 6, … 24 h	Every 24 h at 12 h UT	t−12…33 h	12 hrs	UT1–UTC	3 µs
					Polar motion	45 µas
					Nutation offsets	45 µas
Intermediate with batch correlation of 3 or 24 h blocks	Every 3 h at 3, 6, … 24 h	Every 24 h at 12 h UT	t−12…33 h	3–6 days	UT1–UTC	3 µs
					Polar motion	45 µas
					Nutation offsets	45 µas
Final	Every 3 h at 3, 6, … 24 h	Every 7 d on day 3 at 12 h UT	t−3d…t−10d	7 days	UT1–UTC	1 µs
					Polar motion	15 µas
					Nutation offsets	15 µas
					Telescope coordinates	3 mm
					Source positions	15 µas

ities of the analysis software packages. According to the VGOS Observing Plan (Petrachenko et al., 2013) both the number of stations and the number of observations per baseline will increase considerably compared to the current legacy X/S observing. For a 24-station network and two observations per baseline per minute the total number of delay observations may be close to 800,000. Assuming the current analysis method of least squares adjustments in a Gauss-Markov model with 20-minute atmosphere and clock parameterization, the number of parameters will be close to 4,000. Analyzing this amount of data is not difficult for modern computers, but it will result in some increase in processing time if computing capability or processing algorithms are not improved.

On the other hand, there are other adjustment methods, such as filter techniques, which process the observations sequentially. However, for combination purposes of intermediate results of multiple analysis centers, adjustments with normal equation systems are still the primary choice because these can be produced void of any datum.

In any case, the vast number of observations will preclude manual interaction with the data for editing such as outlier elimination or specification of clock jump location. Currently, analyzing a standard 24-hour session with 10,000 observations takes on the order of 15 minutes if there are no problems. Clearly it would be impractical to analyze a session with 800,000 observations in the same way. This leads to the conclusion that significant effort must be expended to automate this process.

4 Institutional Relations

The existing links of the IVS to institutions and organizations document the strong relationships of the IVS to many activities in various fields. Some of them are very close due to mutual dependencies, others are weak, and some are non-existent even though there seems to be an obvious need for close cooperation. The more formal the links are between the IVS and institutions, associations, and other services, the better it is for its general recognition. The IVS should cooperate with the GGOS project of the IAG and with the UN-GGIM initiative (Global Geospatial Information Management) with its push towards a Global Geodetic Reference Frame (GGRF). These activities will definitely have great benefit for the IVS. Lastly, it should be a declared goal of the IVS and its associates to establish and strengthen further contacts to institutions making direct or indirect use of IVS products to sensitize them to what the IVS has provided. For this reason, active steps to establish contacts and cooperative endeavors with more external institutions using IVS products should be taken by many more IVS associates than is currently the case.

5 Visibility, Public Relations, and Outreach

In the end, it needs to be stressed that public, scientific, and institutional visibility is a fundamental requirement for all components of the IVS. This not only helps to safeguard current funding levels of IVS components but often affects decisions on the pure continuation of operations or investments in new hardware and personnel. These issues begin with observatories running radio telescopes, but also affect coordinating and operations centers, and have a severe effect on correlators. In particular, radio telescopes and correlators are integral parts of VLBI, while coordinating and operations centers provide the organizational structure of the IVS, just to name a few IVS components. All of them need and deserve an appropriate level of visibility. No institution will maintain or build observing or correlator capabilities and finance personnel and infrastructure for operational aspects if they do not benefit from the success of the observations and the results.

At present, almost all publications of IVS results in the scientific literature are authored by colleagues in the IVS Analysis Centers. We are of course glad that our data are used extensively for scientific achievements, but all parts of the IVS that are doing the basic work, which is not less demanding scientifically, are left unrecognized.

A first step to correct this is the introduction of Digital Object Identifiers (DOI numbers) for the data sets of the IVS, which should be used extensively in all publications using IVS data. However, even more important is recognition in scientific publications. While such references in publications by non-IVS scientists might have the highest value, this practice should begin with those IVS colleagues using IVS data for their publications.

Finally, outreach and public relations should be addressed as well. Although mentioned in previous sections concerning institutional relations, the general public should also be offered paths to information, in particular on the IVS Web sites and in dedicated brochures. Beyond regular IVS schools on VLBI, this may also help to attract young people to the field of geodetic and astrometric VLBI.

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